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A Novel Design of Interval Type-2 Neuro-Fuzzy Controller for Flexible Structure

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1. Introduction

Vibration controls against disturbances such as earthquake accelerations are important in the design of the flexible structures. Generally, the methods for vibration control are categorized as active and passive vibration control approaches [1-3]. Although application of the passive control methods is easy and economical, the reported works in the literature indicate that the active control methods are more effective in terms of decreasing the vibration of structures under disturbance effects [4-25]. Mahmoud et al. [5] tested the optimal control approach for vibration control of a building. They designed an optimal controller and presented the advantage and effectiveness of the active controller. An aseismic structural control is researched using fundamental control approach by Yamada et al. [6], presented the effect of feedback and feed forward control rules. Li et al. [7] developed a multiplex structures model under wind and earthquake forces and realized open and closed loop control rules for the structure. Meirovitch and Stemple [8] considered the modeling and active control of spread structures. Zhu et al. [9], researched the interaction control for parallel structures to decrease vibrations. Akhiev et al. [10] presented an optimal control of a structure under earthquake forces. Model predictive control with active mass damping using acceleration feedback of structures is investigated by Mei et al. [11]. Djedoui et al. [12] applied an active hybrid closed loop control to decrease the vibrations of the structure under earthquake accelerations. They achieved 15% reduction in base acceleration and 70% reduction in displacement and velocity. Xu et al. [13], proposed active tuned mass dampers for vibration control of building structures under seismic forces. Braz-César et al. [14] used a Magnetorheological (MR) damper to reduce the seismic response of a single degree-of-freedom (SDOF) framed structure by a semi-active fuzzy based control system. They reported the effectiveness of aforementioned system on the reduction of SDOF structure response. Mitchell et al. [15], implemented genetic algorithm based a fuzzy logic controller to reduce the vibration of a highway bridge against various earthquake loads. Design of the linear quadratic regulator (LQR) and the proportional-integral-derivative (PID) controllers for a flexible structural system under earthquake accelerations was investigated by Tinkir et al. [16]. They reported that PID controller was one step ahead of LQR controller according to displacement criteria both in simulation and experiments. Şen et al. [17] presented the bees algorithm based optimization of PID controller for a two-floors structure under seismic excitation. In their study, PID controller performance was developed changing the objective function and the optimization range of the bee algorithm parameters, and very sufficient results were obtained with their proposed active vibration controller. Nevertheless, intelligent and expert based fuzzy logic controllers are considered to be effective tools for control of nonlinear complex systems such as multi-degree of freedom of structural systems with vibration damping problems [18-27]. Additionally, the reported works also show that the genetic algorithm and robust based fuzzy logic controllers have very successful results on the same issue [28-31].

Most of the research reported on this matter focuses on the effectiveness and practicability of new fuzzy concept as interval type-2 control methodology over vibration control [32-37]. Type-2 fuzzy logic due to containing an inferior membership function and a superior membership function controls uncertainty and imprecision in a best way [38-43], and a type-1 fuzzy set membership function is used to create these two functions. The footprint of uncertainty which is utilized to define a type-2 fuzzy set is indicated by the interval between these two functions. Fuzzy logic controller is utilized in applications since the inherent uncertainty in the acquiring a satisfactory result is difficult. Therefore, the fuzzy logic controller has become a well-known technique and some of the reported investigations in literature on the control of non-linear systems consider adaptive or non-adaptive fuzzy control and interval type-2 fuzzy controller [32-43]. Nayak et al. [32] investigated comparative effective analysis of interval type-2 fuzzy-PID controller with and without derivative filter, type-1 fuzzy-PID controller and conventional PID controller for automatic generation control in a two area interconnected thermal power system. They used a novel adaptive symbiotic organism search and optimization techniques to design the proposed controllers and they concluded that symbiotic organism search optimized interval type-2 fuzzy-PID controller outperformed other proposed controllers in terms of less undershoot, overshoot and settling times. Bathaei et al. [33] presented semi-active seismic control of an eleven degree of freedom building model with tuned mass damper (TMD) and adaptive magnetorheological (MR) damper using type-1 and -2 fuzzy algorithms. They found that the performance of the proposed type-2 fuzzy controller is more effective than the type-1 fuzzy control for decreasing displacement, acceleration, and base shear of the structure. Trajectory and vibration control of a flexible joint manipulator was also investigated by Kelekçi and Kizir [34] using interval type-2 fuzzy logic. In the scope of their study, the proposed controller is designed on the Mamdani based interval type-2 fuzzy logic toolbox using interval triangular membership functions and Karnik–Mendel type reduction algorithm. They reported improved vibration and trajectory tracking behavior of the flexible link with interval type-2 when compared to the conventional type-1 fuzzy logic controllers. Interval type-2 fuzzy vibration control of an electro-rheological fluid embedded smart structure was investigated by Lin et al. [35] and it was concluded that internal type-2 fuzzy is better than the traditional type-1 fuzzy control in terms of vibration reduction of the smart structure. Also Lin et al. [36] studied vibration control design for a plate structure with actively tunable vibration absorbers using interval type-2 fuzzy system. In their study, solution methods of the fuzzy modeling for design, performance analysis, and optimization of harmonic vibration of thin plates were realized. In the research conducted by Moradi et al. [37] a smart digital phase-locked loop (DPLL) for robust carrier tracking systems was investigated using uncertain rule-based interval type-2 fuzzy (IT2) controllers. They designed IT2 fuzzy controllers to determine optimal DPLL loop filter coefficients resulting in bandwidth to reject noise, handle user dynamics, and sustain locked. After DPLL simulation with Xilinx System Generator, they reported effective responses to various test signals such as phase and frequency steps, frequency ramp and added sinusoidal jitter stimuli with fast acquisition and improved pull in range.

Although interval type-2 fuzzy logic based control approaches have been investigated by many researches as referenced above, a novel design of the IT2NF controller has not been proposed yet for control application on proposed flexible structures using both simulation and experimental methods. Therefore, the motivation of this work is to come up with a novel design of interval type-2 neuro-fuzzy (IT2NF) controller for active vibration control of two-storey flexible structure against earthquake excitations. Accordingly, two adaptive neural network based fuzzy logic controllers are designed and combined to create an IT2NF controller to reduce the vibrations of flexible building model that occurs during earthquake effect. Additionally, the proposed system is simulated and compared with the experimental results to determine the effectiveness and performance of the proposed controller. Moreover, comparative performance analysis of IT2NF controller is performed based on the simulation and experimental results with respect to cart displacements, deflections, and accelerations of the flexible floors.

2. Dynamic modeling of the flexible structure

A flexible structural system model is developed to simulate the dynamic behavior and active vibration control of the building under an earthquake excitation. A system is designed for the control problems raised in structures similar to the nature where the weight constraints result in flexible structures that have to be controlled using feedback techniques. Fig. 1 illustrates the discrete system model and experimental setup including a cart, two floors and a shaker system developed and used in this study. In the given figure, k_1-k_2 and b_1-b_2 are the stiffness and damping coefficients of the first and second floor, respectively. k_c and b_c are stiffness and damping coefficients of the shaft to which the car is attached. F_c is described as control force of the cart. The masses and displacements of the flexible floors are given with m_1, m_2, x_1 and x_2, respectively. The cart assembled on the top floor with gear system acts as an active mass damper (AMD). AMD slides on the bar along horizontal axis. The role of the cart is to decrease the vibrations originated from the shaker motion. The positive directions of horizontal displacement and acceleration $\ddot{X}_g$ of the ground motion provided by shake table are towards the right as given in Fig. 1. Two accelerometers are placed on the system to measure the tip deflections of floors of the system.

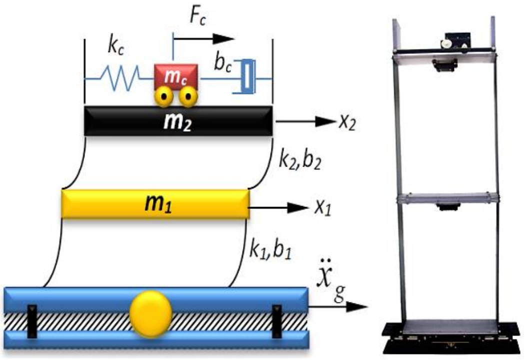


Fig. 1 Discrete system of the model (left) and the experimental setup (right) of the two-storey building

The equation of the motion of the discrete model can be defined as state-space representation given in Eq. (1).

$$\dot{X} = AX + BU + \ddot{X}_g \text{ and } Y = CX + DU, \tag{1}$$

where: X is state variables vector and its transpose is written as follows:

$$X^T = \begin{bmatrix} x_c & x_1 & x_2 & \dot{x}_c & \dot{x}_1 & \dot{x}_2 \end{bmatrix}. \tag{2}$$

Also x_c is the cart linear position relative to the second floor, x_1 and x_2 are displacements of the floors. Moreover, output vector Y is presented as follows:

$$Y^T = \begin{bmatrix} x_c & \ddot{x}_1 & \ddot{x}_2 \end{bmatrix}. \tag{3}$$

In Eq. (4), the driving force of the cart F_c is equal to cart's DC motor voltage V_m and defined as the input U in Eq. (1).

$$U = F_c = V_m. \tag{4}$$

The equation of motion of the discrete system model is also simulated in MATLAB/Simulink for verification of the created model. On the other hand, SolidWorks software is used to draw the flexible structure system, shake table module and cart with geometric configuration and mechanical properties in terms of the experimental setup specifications. Additionally, solid model of the system is imported to MATLAB/SimMechanics software for the development of modeling technique. In MATLAB/ SimMechanics, the flexibility of the floors is defined by considering stiffness and damping coefficients and each flexible floor is separated into ten bodies with custom joints which rotate only on z axis. Joint sensors and joint actuators are added and angle and angular velocity feedbacks are measured using joint sensor blocks. Moreover, these feedbacks are linked with stiffness and damping coefficients. The stiffness and damping forces are used for input of the joint actuator which actuated custom joint during simulations. The stiffness and damping coefficients of the material used in the experimental setup (stainless steel with a dimension of 500x110x1.75 mm) are calculated using the values reported in the literature [44-46]. Neves et al. [44] investigated the dynamics of a cantilever beam and a beam free of support conditions. They compared their results with exact solutions and with experimental data from the literature. Comparative study of damping in pristine, steel, and shape memory alloy (SMA) hybrid glass fiber reinforced plastic (GFRP) composite beams of equivalent stiffness was presented by Gupta et al. [45]. In this study, damping ratio was measured experimentally through logarithmic decay method and through experiments damping ratio obtained for SMA hybrid composite beam was found to be higher as compared to the pristine and steel hybrid GFRP composite beams. Also Hunt et al [46], researched that cantilever beam static and dynamic response comparison with mid-point bending for thin medium density fiberboard (MDF) composite panels. As a result of their paper, the damping ratio for the cantilever beam was calculated using the log decrement of the displacement. According to [45], the vertical deflection w of the cantilever beam is written as follow:

$$w = \frac{PL^3}{3EI}. \tag{5}$$

The flexural stiffness K is described as:

$$K = \frac{3EI}{L^3}, \tag{6}$$

where: P is load; I is the moment of inertia; E is the longitudinal Young's modulus; L is the length of beam; b is the width of beam; t is the thickness of beam. For stainless steel E (Young modulus) is 2.10^{11} Pa. For beam with rectangular cross section's moment of inertia is as:

$$I = \frac{bh^3}{12}. \tag{7}$$

The Eqs. (6) and (7), are calculated as $b = 110$ mm, $h = 1.75$ mm and $L = 500/10$ mm (therefore, each floor is separated into ten flexible bodies). In addition to these calculations and to verify, finite element (FE) model is constituted in Fig. 2 for stainless steel cantilever beam, and stiffness and damping coefficients are found as $K = 260$ N/mm and $B = 0.02$ N.s/mm.

According to literature and calculations, the properties of the experimental system such as material, stiffness, inertia etc. are assigned to the model in Matlab/ SimMechanics. Fig. 3 shows modeling steps and SimMechanics model.

This modeling approach is provided to obtain the similar model which is convenient to experimental setup of the proposed system. In this modeling, differential equations which are mostly used to find the equation of the motion of the systems are not required anymore and rigid body calculations are converted to flexible body using discrete system model, cantilever beam equations and finite element model. The flexibility of the proposed SimMechanic model is given in Fig. 4.

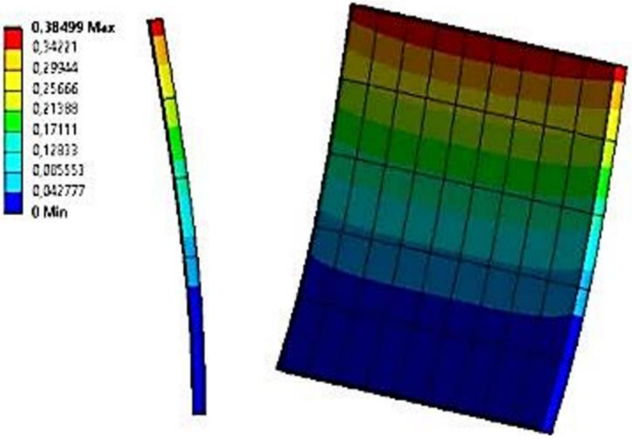


Fig. 2 FE model of the stainless steel cantilever beam

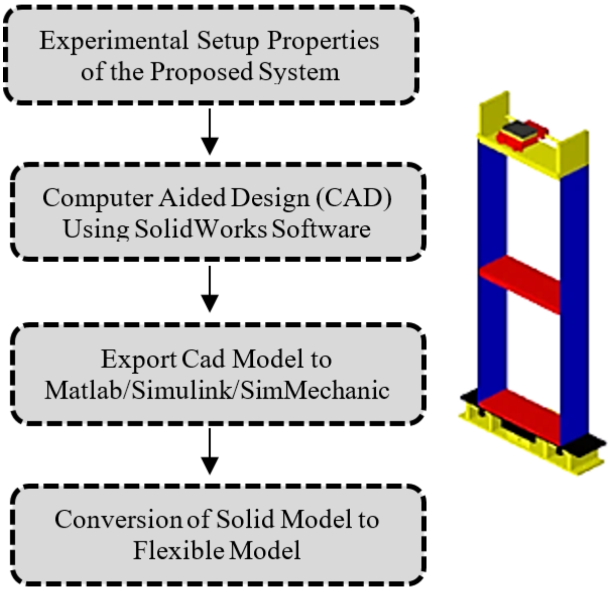


Fig. 3 The modeling steps and SimMechanics solid model

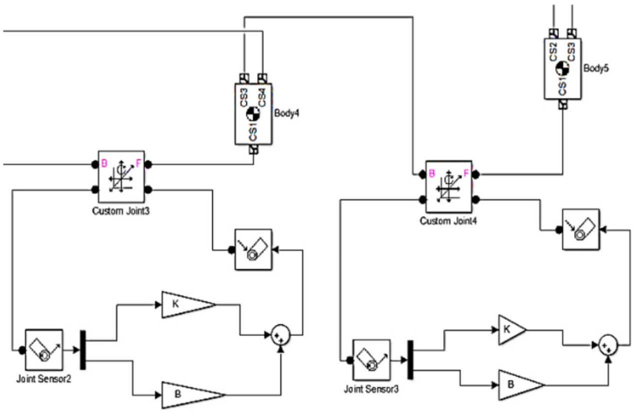


Fig. 4 The flexibility of SimMechanics model

3. The design of IT2NF controller

Type-2 fuzzy are utilized to control uncertainty and instability successfully which was defined and proposed by Zadeh [47-48]. Type-2 is characterized with an inferior membership function and a superior membership function which can be presented by a type-1 fuzzy membership function [49-52]. Traditionally, type-1 fuzzy logic controllers have been considered widely in control of nonlinear systems. In recent years, it has been found that the type-1 fuzzy logic controllers (FLC) are not sufficient to control uncertainties of the systems [53-58]. The membership function (MF) of a type-2 fuzzy set is three dimensional which includes a footprint of uncertainty. It provides additional degree of freedom that makes it possible to handle the uncertainties as compared to type-1 fuzzy. The reported studies [38-43] show that manually designing and tuning a type-2 FLC gives better response when the number of MF parameters rises.

In this paper, initially, close-loop feedback behavior of flexible structure against scaled Northridge acceleration is simulated to create appropriate artificial neural network base of proposed IT2NF controller for experimental control application. For this purpose, two adaptive neural networks based fuzzy logic controllers are designed with different type of membership functions as gauss, triangular and also these controllers are combined to create an IT2NF controller. The design of two fuzzy logic controllers is realized using artificial neural network based fuzzy inference system. A hybrid learning algorithm is used to identify the parameters of Sugeno-type fuzzy inference systems. A combination of back propagation gradient descent method and least-squares method are applied to train membership function parameters of the fuzzy inference system.

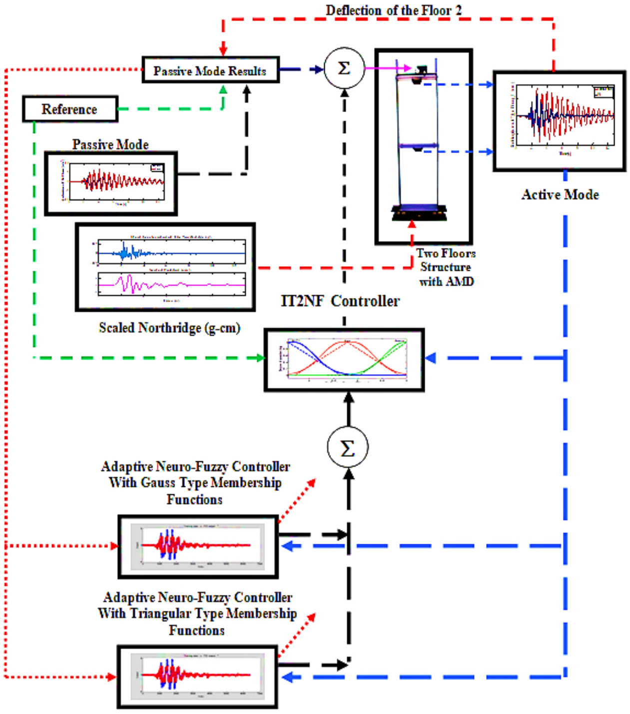


Fig. 5 Block diagram and control methodology of scaled flexible structure

Fig. 5 shows the control methodology and block diagram of a flexible structure controlled by an IT2NF controller under the earthquake excitations.

Many types of membership functions are examined in this study, and three gauss and triangular membership functions are utilized for deflection error of second floor as shown in Fig. 6. The membership functions include negative, zero and positive. The rule bases of each artificial neural network based fuzzy logic controllers (ANNFLC) are composed of 10 rules. Artificial neural network based fuzzy inference system grantees acquiring an optimum range of membership functions. For instance, the rule base of ANNFLC is described as follow; when the deflection error of floor 2 is negative the control voltage becomes V_m as [-1.952 0.06804]. The ANNFLC architecture consists of five layers with the output of the nodes in each respective layer is represented by $O_{i,l}$ where i is the ith node of layer l.

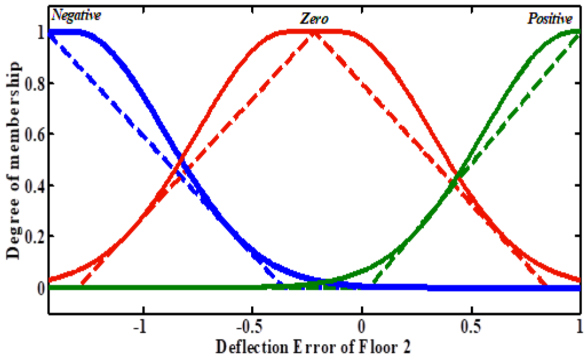


Fig. 6 The membership functions of the proposed IT2NF controller

Layer 1. Generate the membership grades:

$$O_{i,l} = \mu_{A_i}(x)\,,\ i = 1,2, \tag{8}$$

$$O_{i,l} = \mu_{B_i\,2}(y)\,,\ i = 3,4, \tag{9}$$

where: x (or y) is the input to the node and A_i (or $B_{i\text{-}2}$) is the fuzzy set associated with this node.

Layer 2. Generate the firing strengths by multiplying the incoming signals and outputs the t-norm operator result, e.g.:

$$O_{2,i} = w_i = \mu_{Ai}(x) \times \mu_{Bi}(y)\,,\ i = 1,2. \tag{10}$$

Layer 3. Normalize the firing strengths:

$$O_{3,i} = \overline{w_i} = \frac{w_i}{w_1 + w_2}\,,\ i = 1,2. \tag{11}$$

Layer 4. Calculate the rule outputs based on the consequent $\{p_i, q_i, r_i\}$ parameters:

$$O_{4,i} = \overline{w}_i f_i = \overline{w}_i (p_i x + q_i y + r_i). \tag{12}$$

Layer 5. Computes the overall outputs as the summation of incoming signals:

$$O_{5,l} = \sum_i \overline{w}_i f_i = \frac{\sum_i w_i f}{\sum_i w_i}. \tag{13}$$

The proposed IT2NF controller includes as follows:

- 3500 and 500 datum is used for training and checking, respectively.
- 100 epochs are used to train hybrid learning algorithm

The hybrid learning algorithm given above is defined in the literature [49-58]. In the forward pass of the hybrid learning algorithm, node outputs go forward until layer 4 and the consequent are identified by the least-squares method. The adaptive neural network base fuzzy inference system is a fuzzy Sugeno model put in the framework of adaptive systems to facilitate learning and adaptation [38-43]. Such framework makes the adaptive neural network base fuzzy inference system control more systematic and less reliant on expert knowledge. To present the adaptive neural network base fuzzy inference system architecture, two fuzzy IF-THEN rules based on a first-order Sugeno model are considered as follows:

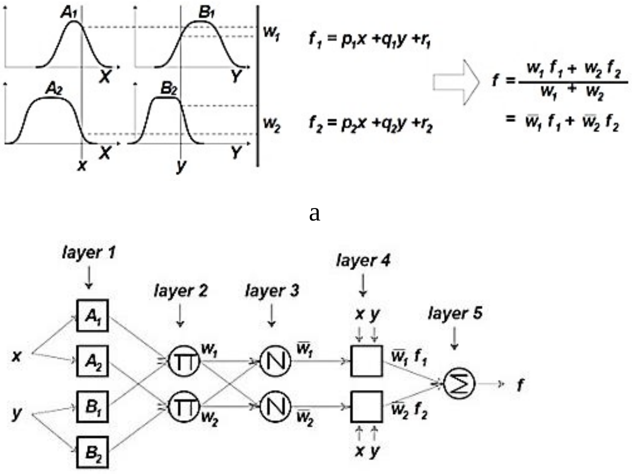
Rule 1: If (x is A_1) and (y is B_1) then ($f_1 = p_{1x} + q_{1y} + r_1$)

Rule 2: If (x is A_2) and (y is B_2) then ($f_2 = p_{2x} + q_{2y} + r_2$)

where: x and y are the inputs; A_i and B_i are the fuzzy sets; f_i are the outputs within the fuzzy region specified by the fuzzy rule; p_i, q_i and r_i are the design parameters that are determined during the training process [38-39].

$$f = \frac{w_1}{w_1 + w_2} f_1 + \frac{w_2}{w_1 + w_2} f_2 = \overline{w}_1 f_1 + \overline{w}_2 f_2 = (\overline{w}_1 x) p_1 + \\ + (\overline{w}_1 y) q_1 + (\overline{w}_1) r_1 + (\overline{w}_2 x) p_2 + (\overline{w}_1 y) q_2 + (\overline{w}_1) r_2. \tag{14}$$

The adaptive neural network base fuzzy inference system architecture to implement these two rules is shown in Fig. 7, in which a circle indicates a fixed node, whereas a square indicates an adaptive node [38-39].



a

b

Fig. 7 a) Takagi-Sugeno-Kang (TSK) fuzzy inference system with two inputs and two rule; b) Architecture of adaptive neural network base fuzzy inference system of first order TSK model with two inputs

4. Experimental setup

Experimental setup of the flexible structural system includes two flexible floors; shake table (The Quanser Shake Table I-40), and a cart [59]. Briefly, floors of the system are installed on shaker, and disturbance input is performed using shake table same as seismic excitation. Moreover, AMD is a cart that moves in linear direction and installed on the top floor and, it is employed to suppress the structural vibrations and deflections in active mode. The schematic diagram of experimental setup is given in Fig. 8. The geometric configuration of each floor of the system is 0.50 m, 0.32 m, and 0.11 m, for the height, length, and depth, respectively. The geometrical parameters of cart are defined as 0.31 m, 0.13 m, and 0.11m, for the height, length, and depth, respectively. The other requirements of the experimental setup are two UMP 1503 power modules, Q8 terminal board cart, PC and MATLAB/Simulink software. The shake table includes a high torque direct drive motor which can drive a 5 kg mass at 1 g. The maximum travel is ± 20 mm. Shaker is utilized to form disturbances, simulate earthquakes (up to 10 Hz) and check the performance of AMD [59]. The geometric configuration of shaker is 0.508 m length, 0.152 m width, 0.089 m height and 10.8 kg total mass. Floors of the system are fabricated from two identical single-story modules which assembled on top of each other. Every single-storey moduli consists of two vertical stainless steel beams. The steel beams have a section with 1.75 mm x 110 mm dimensions and 0.240 kg mass.

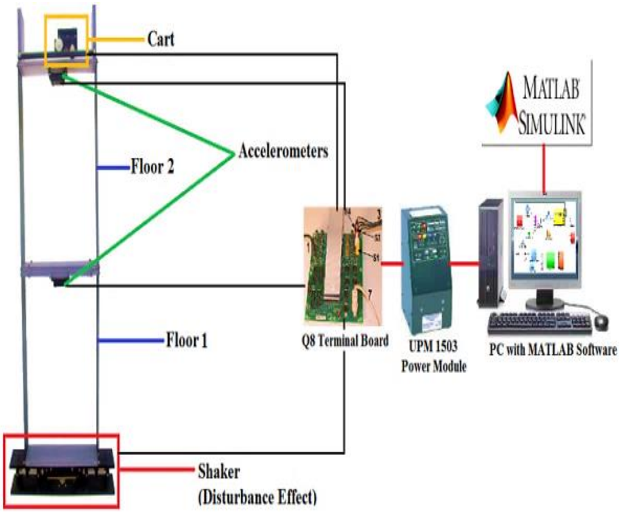
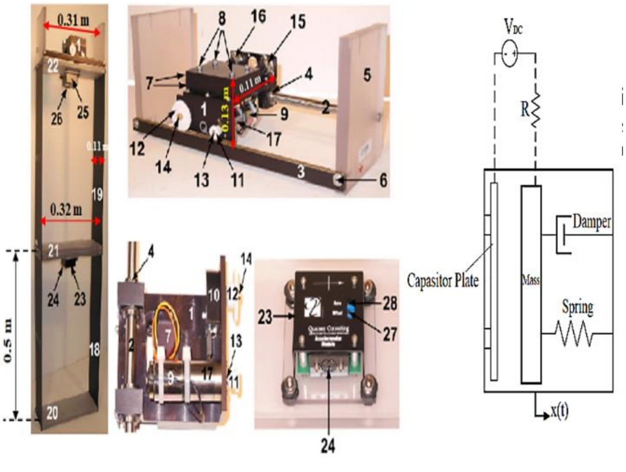


Fig. 8 The experimental setup of the proposed system



a

b

Fig. 9 a) The description of the flexible structure; b) the physical model of the DC accelerometer

Each floor is equipped with a capacitive DC accelerometer with full-scale range of ± 5 g with signal conditioning. The accelerometers are capable to measure the AC/dynamic acceleration and DC/static acceleration. In order to provide an accurate measurement of the vibration, the accelerometers are mounted in longitudinal directions on the floors of the system. The description of the flexible structure is shown in Fig. 9, a and Table 1. The physical model of the accelerometer is given Fig. 9, b.

Table 1

The description of the flexible structure and cart

ID	Description	ID	Description
1	Cart	2	Stainless steel shaft
3	Track	4	Linear bearing
5	Rack end plate	6	Rack set screw
7	Cart load weight	8	Cart load weight set screw
9	Cart DC motor	10	Cart encoder
11	Cart motor pinion	12	Cart position pinion
13	Cart motor pinion shaft	14	Cart position pinion shaft
15	Cart motor connector	16	Cart encoder connector
17	Cart planetary gearbox	18	Floor 1 flexible structure
19	Floor 2 flexible structure	20	Ground floor
21	Floor 1	22	Floor 2
23	Floor 1 accelerometer	24	Floor 1 accelerometer connector
25	Floor 2 accelerometer	26	Floor 2 accelerometer connector
27	Accelerometer offset potentiometer	28	Accelerometer gain potentiometer

5. Results and discussion

The Northridge earthquake happened on January 17, 1994, at 04:31 Pacific standard time in Reseda, in Los Angeles, California. The acceleration of ground was measured 1.7 g (16.7 m/s^2) which was one of the highest earthquakes recorded in an urban in North America. The Northridge earthquake had a maximum displacement of 16.92 cm which is scaled down to 1.5 cm (set as x_{max}) in this study.

In order to obtain the same acceleration as Northridge, the time period is shortened from 39.98 to 11.91 seconds as suggested in [60]. Fig. 10 displays the recorded earthquake acceleration in gravitational units and the scaled position set point (in centimeters) for the Northridge earthquake. Captured simulations and flexibility of the floors obtained from MATLAB/SimMechanics model are given in Fig. 11.

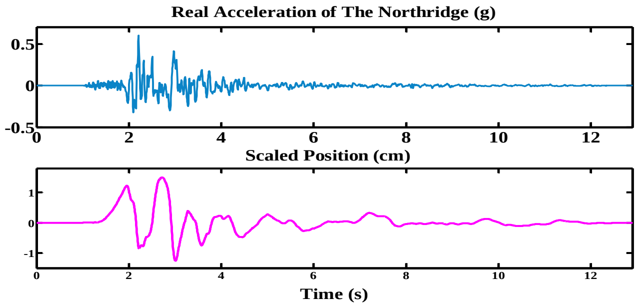


Fig. 10 Real acceleration and scaled position of the Northridge earthquake

The deflection results of the floors in passive mode simulations are shown in Fig. 12. As seen in Fig. 12, maximum deflections of first and second floor in passive mode are acquired as 1.9 cm and 3.1 cm, respectively. The second floor deflection is more than the first-floor response because deflection is increased by bending moment via height of the structure. Also maximum deflections of the floors occur between 2 and 4 seconds under the Northridge Earthquake. After 4 seconds the deflections decreased step by step.

The deflection results of IT2NF controlled simulation model are given in Figs. 13-14. From these simulation results the following; the values of total deflection of the floors are lower than passive mode deflection responses and maximum floor deflections are evaluated for IT2NF controlled system as floor 1 is 1.1 cm and floor 2 is 1.8 cm. Fig. 15 shows the displacement of IT2NF controlled cart in simulations. Maximum displacement of cart is obtained as 5.6 cm.

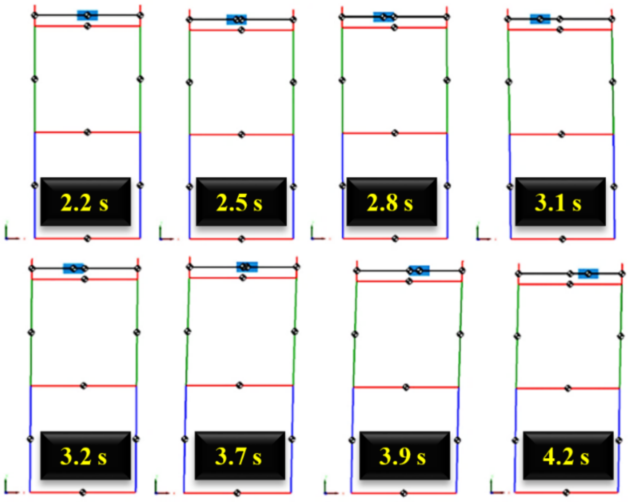


Fig. 11 Animations of simulation model against to Northridge Earthquake in passive mode

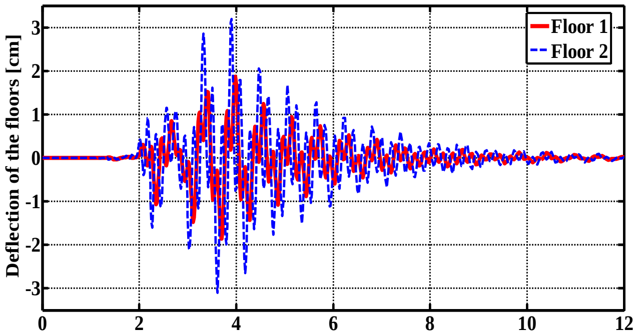


Fig. 12 Passive mode deflection results in simulations

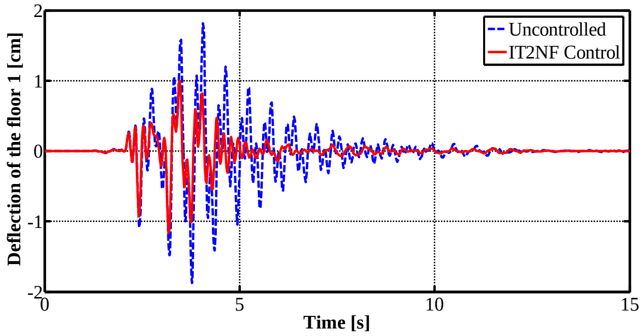


Fig. 13 The deflection comparison of uncontrolled and IT2NF controlled system for floor 1 in simulations

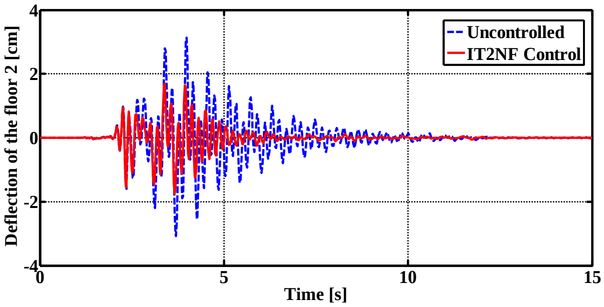


Fig. 14 The simulations showing the deflections of uncontrolled and IT2NF controlled system for floor 2

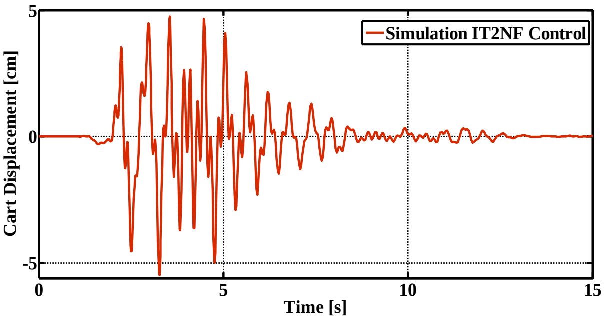


Fig. 15 IT2NF controlled cart displacement in simulations

In active mode, experimental results of IT2NF controlled system are given in Figs. 16 and 17. As seen, maximum deflections of the first and second floor in passive mode are acquired as 2.1 and 3.3 cm, respectively. From these experimental results, maximum floor deflections are evaluated for IT2NF controlled system as 1.8 and 2.4 cm for the first and second floor, respectively. The experimental acceleration results of passive mode and IT2NF controlled the floors are given in Figs. 18 and 19. As seen in Fig. 18, first and second floor maximum acceleration in passive mode are obtained as 6.5 and 7.1 m/s^2, respectively. In active mode, experimental acceleration results of IT2NF controlled system given in Fig. 19 are obtained for first and second floors as 5.2 and 7.8 m/s^2, respectively. When the passive and active mode acceleration results are compared, it is possible to say that an acceleration response in passive mode continues as oscillations affecting the deflection responses of the floors in the same mode. The displacement and voltage of IT2NF controlled cart in experiment are given in Figs. 20-21.

Maximum cart displacement is obtained as 6.15 cm. and IT2NF controlled cart voltage is found as 2.7 V.

According to given figures based simulation and experimental results; the following discussions are derived as:

- The experimental results verified that novel design IT2NF controller decreased the total deflections of first and second floors by 72.3% and 68.7%, respectively in comparison to uncontrolled responses.
- The experimental results proved that novel design IT2NF controller reduced floor 1 total accelerations by 64.8% and floor 2 total accelerations by 54.6% in comparison to uncontrolled results.
- It is concluded that novel design IT2NF controller is very successful in terms of active vibration control of the flexible structure under disturbance effect such as earthquake excitation. Also the numerical comparison of simulation and experimental results is given in Table 2.

Table 2

The comparison of the results

Approaches	Simulation		Experimental	
Maximum deflection results	Floor-1, cm	Floor-2, cm	Floor-1, cm	Floor-2, cm
Passive (Uncontrolled)	1.9	3.1	2.1	3.3
IT2NF Controlled	1.1	1.8	1.8	2.4

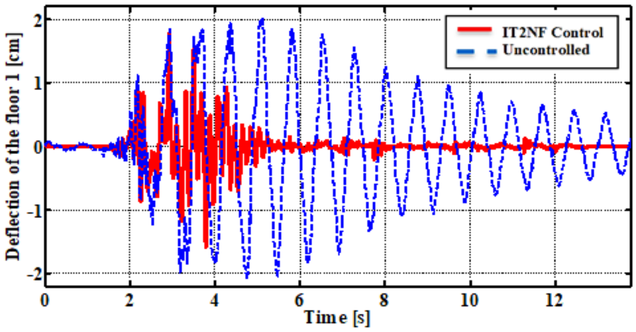


Fig. 16 The deflection comparison of uncontrolled and IT2NF controlled system for floor 1 in experiments

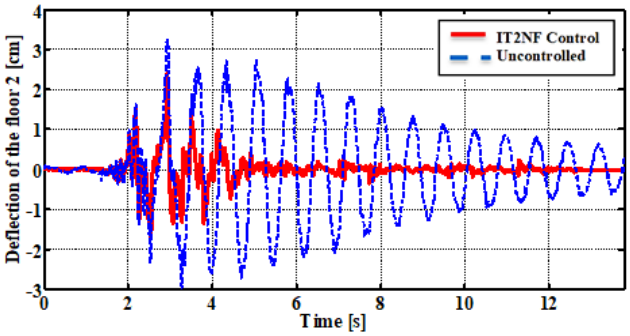


Fig. 17 The deflection comparison of uncontrolled and IT2NF controlled system for floor 2 in experiments

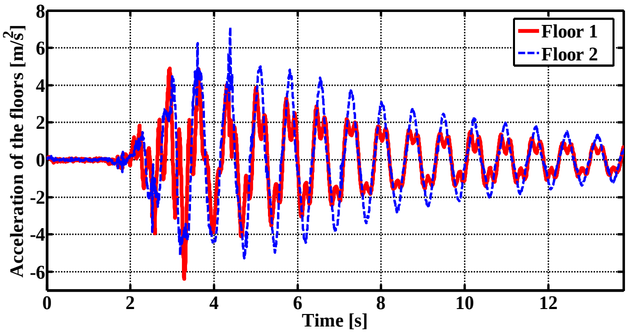


Fig. 18 Passive mode experimental acceleration results

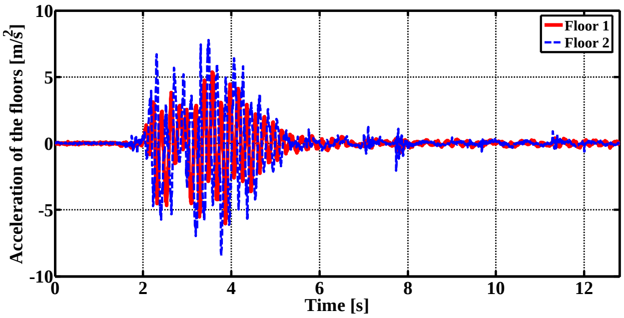


Fig. 19 IT2NF controlled mode experimental acceleration results

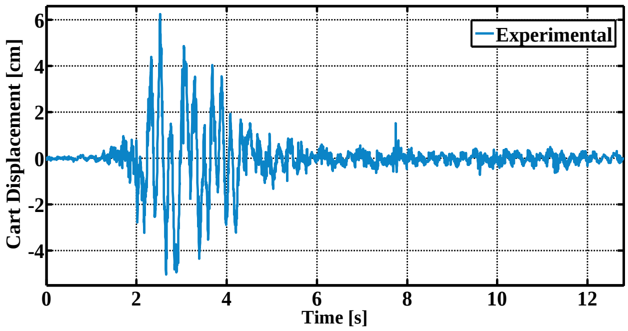


Fig. 20 IT2NF controlled cart displacement in experiments

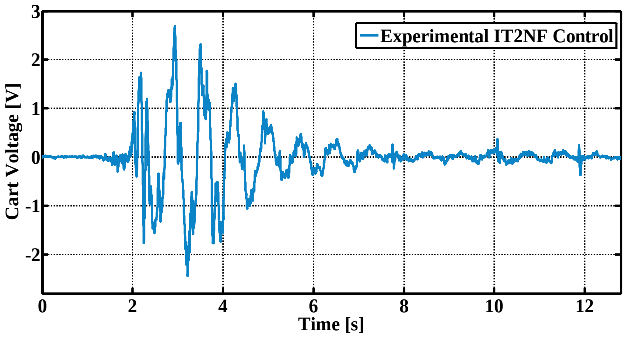


Fig. 21 The change of cart voltage in active mode

6. Conclusions

The active control methods for the disturbances are shown to be more effective than the passive controllers in terms of decreasing the vibration of structures under disturbance effects. In this study, a novel design of interval type-2 neuro-fuzzy (IT2NF) controller is proposed for active vibration control of a flexible structure during an earthquake. A combination of the dynamic model and simulations are carried out to determine the performance of the proposed controller, accordingly experimental setup is established to verify the accuracy of the simulated models. The experimental results reveal a respectable reduction both in the total deflections and the accelerations of the floors under the scaled Northridge Earthquake accelerations. The active controller is proposed and designed in this study can be seen as an alternative an active vibration controller for multi-degree of freedom of flexible systems under the disturbances such as earthquake excitations.

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A NOVEL DESIGN OF INTERVAL TYPE-2 NEURO-FUZZY CONTROLLER FOR FLEXIBLE STRUCTURE

Summary

The aim of this research is to develop a novel design of interval type-2 neuro-fuzzy (IT2NF) controller for active vibration control of a flexible structure during an earthquake. For this purpose, two adaptive neural network based fuzzy logic controllers are designed and combined to create the novel design of an IT2NF controller to reduce the vibrations of two-storey flexible building model that occur during earthquake disturbance effects. Accordingly, dynamic modeling of a flexible structure is realized and simulated using the MATLAB / SimMechanics. Then, an experimental setup consisting of two-storey flexible structure, active mass damper (AMD) and shaker is established. Additionally, IT2NF controller is implemented in simulation and experimental models, and the effectiveness and performance of the IT2NF controller are tested under the scaled Northridge Earthquake acceleration. The obtained simulations and experimental responses are evaluated in terms of cart displacements, deflections, and accelerations of the flexible floors showing a good agreement between the simulations and the experimental results. The results show that the designed novel IT2NF controller reduced the total deflections of first and second floor by 72.3% and 68.7%, respectively, when compared with the uncontrolled system. Additionally, it is also found that the designed IT2NF controller is able to reduce the accelerations of the first and second floor by 64.8% and 54.6%, respectively. The proposed and designed control method reported in this study can be employed as an active vibration controller for multi-degree of freedom of flexible systems under the disturbances such as earthquake excitations.

Keywords: interval type-2 neuro-fuzzy control, flexible structure, active vibration control, modeling and simulation, experimental.

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